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5 The present invention relates to semiconductor devices having ridge structure, such as the ridge-type semiconductor laser devices. The ridge structure may be formed on top of a surface of a substrate, or within a surface of a substrate, as in the case of double channel semiconductor devices, such as Double Channel Planar Buried Heterostructures.

Conventionally, semiconductor devices having
15 desired electric circuitry or desired electric elements
have been formed by forming a multi-layer film structure
on a semiconductor substrate and then performing etching
or the like.

This semiconductor laser device has a lower clad layer 3, an active layer 4, an upper clad layer 5, a contact layer 9 and an insulating film 6 sequentially formed on the upper face of semiconductor substrate 2. A

part of the upper clad layer 5, contact layer 9 and the insulating film 6 together form ridge 12'. In addition, a negative electrode 1 is formed on the lower face of the semiconductor substrate 2, and a positive electrode 7 is
5 formed on the upper face of the semiconductor laser device.

This conventional semiconductor laser device is manufactured with a method that is shown in Fig. 8A to Fig. 8C and Fig. 9A to 9C. As shown in Fig. 8A, the
10 lower clad layer 3, active layer 4, upper clad layer 5 and the contact layer 9 are sequentially formed on one surface of the semiconductor substrate 2. Then, the resist 10 is applied to form a film on the contact layer 9.

15 Thereafter, as shown in Fig. 8B, the contact layer 9 and the upper clad layer 5 are etched by to thereby form the ridge 12' having the same width as that of the resist 10. Subsequently, as shown in Fig. 8C, the resist 10 is removed, and the insulating film 6 is formed on the
20 exposed surfaces of the upper clad layer 5 and the contact layer 9. Thus, the insulating film 6 completely covers the ridge 12'.

Subsequently, as shown in Fig. 9A, the resist 11 is applied on the insulating film 6. This resist 11 is
25 applied in such a manner that it covers the ridge 12'. Although not shown in the drawing, another resist is formed above the resist 11 thereby making the surface above the ridge 12' and its periphery flat. Thereafter, as shown in Fig. 9B, photolithography and oxygen plasma
30 ashing processing are performed thereto, to remove the resist 11 on the upper face of the ridge 12' and the peripheral portion thereof, up to the height of the

insulating film 6 of the ridge 12', to thereby expose the insulating film 6 on the upper face of the ridge 12'.

Subsequently, as shown in Fig. 9C, the insulating film 6 on the upper face of the ridge 12' is removed by plasma etching processing, to thereby expose the contact layer 9. Then, the resist 11 is completely removed, and the positive electrode 7 (see Fig. 7) is deposited on the entire upper face including the side of the ridge 12'. Finally, the lower face of the substrate is milled and polished to reduce the thickness of the substrate, and the negative electrode 1 (see Fig. 7) is deposited on the lower face of the semiconductor substrate 2. Thus, the conventional ridge-type semiconductor laser device is obtained.

The positive electrode 7 and the negative electrode 1 are each generally formed using a dry deposition process, a plating process, and several photolithography processing steps (resist coating, exposure UV light, resist development, and resist stripping) to define masks for dry deposition process and the plating process. An ionic solution is generally used for developing an image in the resist, and an organic solvent is generally used to strip the photo-resist, although an aqueous alkaline solution (which is ionic) can sometimes be used for stripping, depending upon the composition of the resist. The plating bath used in the plating process is generally an ionic solution.

In the conventional semiconductor laser device, an erosion of the contact layer 9 often occurs when the positive electrode 7 and negative electrode 1 are formed. When the contact layer 9 is eroded, the current channel of the obtained semiconductor laser device becomes narrow

and thereby the electric resistance increases. As a result, there is a drawback that the optical output of the semiconductor laser device decreases. If the erosion is severe, most of the contact layer 9 and the upper clad layer 5 are affected, thereby the optical output further decreases.

The present invention is directed to understanding the causes of this erosion, and to minimizing, and hopefully substantially preventing, the occurrence of the erosion.

SUMMARY OF THE INVENTION

In making their invention, the inventors have recognized that the erosion is caused by cracks within the top positive electrode layer, and the subsequent filling of these cracks with ionic solutions and/or organic solvents from the photo-lithographic process and/or plating process, with the ionic solutions and/or the organic solvents causing the erosion. Furthermore, the inventors believe that the cracks are caused by stresses within the ridge, and that these stresses result from the exposure of the ridge to various temperatures during the various manufacturing processes.

It is an object of the present invention to provide a semiconductor device which reduces these stresses, and which does not have cracks in the positive electrode or erosion of the contact layer.

It is another object of this invention to provide a method by which such semiconductor devices can be manufactured easily and efficiently.

According to the present invention, the ridge is formed by a first semiconductor layer, a second

semiconductor layer, and a third semiconductor layer sequentially from bottom to top, with at least two of the layers having different compositions or properties. When etched by a desired etchant, the first semiconductor layer is etched at a first etching speed, the second semiconductor layer is etched at a second etching speed, and the third semiconductor layer is etched at a third etching speed. The second etching speed is higher than the first etching speed and slower than the third etching speed.

Other objects and features of this invention will become apparent from the following description with reference to the accompanying drawings.

15 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a sectional view of a semiconductor laser device, being one embodiment of the present invention;

Fig. 2A to Fig. 2C are sectional views showing the manufacturing process of the semiconductor laser device shown in Fig. 1 according to the present invention;

Fig. 3A to Fig. 3C are sectional views showing continuation of the manufacturing process of the semiconductor laser device shown in Fig. 1 according to the present invention;

25 Fig. 4 is an enlarged sectional view of a ridge
portion of an exemplary semiconductor laser device
according to the present invention;

Fig. 5 is a diagram showing the distribution of aluminum in the ridge portion according to one embodiment of the present invention;

Fig. 6 is a diagram showing a case where the composition of aluminum in a forward mesa forming layer

changes stepwise according to another embodiment of the present invention;

Fig. 7 is a sectional view of a semiconductor laser device which is an example of a conventional semiconductor device;

Fig. 8A to Fig. 8C are sectional views showing the manufacturing process of the semiconductor laser device shown in Fig. 7; and

Fig. 9A to Fig. 9C are sectional views showing continuation of the manufacturing process of the semiconductor laser device shown in Fig. 7.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Embodiments of the semiconductor device and the manufacturing methods thereof according to the present invention will be explained below in detail, with reference to the accompanying drawings.

Fig. 1 is a sectional view of an exemplary semiconductor laser device according to one embodiment of the present invention. The multi-layer film substrate forming the semiconductor laser device has a lower clad layer 3, an active layer 4, an upper clad layer 5, a forward mesa forming layer 30, a contact layer 9 and an insulating film 6 formed on the upper face of a semiconductor substrate 2. The upper clad layer 5, forward mesa forming layer 30, contact layer 9 and the insulating film 6 together form a ridge 12. Next, a negative electrode 1 is formed on the lower face of the semiconductor substrate 2, and a positive electrode 7 is formed on the upper face of the multi-layer film substrate 31.

Fig. 4 is an enlarged sectional view of the ridge

portion of the exemplary semiconductor laser device according to the present invention. As shown in the figure, the ridge comprises a base, an upper face located above the base, and side faces located between the
5 ridge's upper face and the base. The base is attached to the composite substrate formed by substrate 2, layer 3, layer 4, and the lower portion of layer 5. In general, the ridge according to the present invention may be attached to homogeneous substrate (such as substrate 2)
10 or a composite substrate which comprises many layers, such as shown in Fig. 4. These definitions of base, side face, and upper face of the ridge apply to the ridge as shown in Figs. 1, 2B-2C, 3A-3C, and 5-6. Upper clad layer 5 is a first semiconductor layer of the ridge and
15 is located closer to the base than the upper face of the ridge. Forward mesa forming layer 30 is a second semiconductor layer of the ridge and is located above layer 5 and below the upper face. Layer 30 has a bottom surface located near layer 5 and a top surface located
20 near layer 9. Contact layer 9 is a third semiconductor layer of the ridge and is located above layer 30 and below the upper face.

This semiconductor laser device is manufactured with a process that will be explained with reference to
25 Fig. 2A to Fig. 2C and Fig. 3A to Fig. 3C. As shown in Fig. 2A, the lower clad layer 3 having a composition of n-type AlGaAs, the active layer 4, the upper clad layer 5 having a composition of p-type $\text{Al}_{x1}\text{Ga}_{1-x1}\text{As}$, the forward mesa forming layer 30 having a composition of p-type
30 $\text{Al}_{x2}\text{Ga}_{1-x2}\text{As}$, and the contact layer 9 having a composition of p-type GaAs are sequentially formed on the one surface of the semiconductor substrate 2 having a composition of

n-type GaAs. X1 is the Al-Ga stoichiometric parameter of upper clad layer, and x2 is the Al-Ga stoichiometric parameter of forward mesa forming layer 30.

Stoichiometric parameter X1 is substantially constant,
5 and typically ranges between 0.2 and 0.5, and is preferably between 0.25 and 0.35. In the composition of the forward mesa forming layer 30, stoichiometric parameter x2 is variable which decreases monotonically in value from the bottom surface of layer 30 (which is
10 adjacent to upper clad layer 5) toward the top surface of layer 30 (which is adjacent to contact layer 9). X2 may decrease continuously, or in one or more steps. (As is known in the art, the term "monotonically" means that the value moves in only one direction: (1) the same level or
15 increasing to a higher level, or (2) the same level or decreasing to a lower level.) The various layers may be formed using the thin-film epitaxial growth method such as the MOCVD method or MBE method.

It may be appreciated that instead of comprising
20 GaAs, contact layer 9 may comprise $\text{Al}_{x3}\text{Ga}_{1-x3}\text{As}$, where x3 is relatively small (such as $x3 < 0.05$). In this case, Stoichiometric parameter x3 is preferably substantially constant and substantially less than or equal to the lowest value of the stoichiometric parameter x2 of layer
25 30.

A resist 10 is then applied to form a film on the contact layer 9.

Thereafter, as shown in Fig. 2B, the contact layer 9, the forward mesa forming layer 30 and the upper clad
30 layer 5 are etched by wet etching processing using citric acid type solution to thereby form the ridge 12 having substantially the same width as that of the resist 10.

Subsequently, as shown in Fig. 2C, the resist 10 on the upper face of the multi-layer film substrate 31 is removed by dissolving it using a stripping solution, and any residual of the resist 10 is then completely removed
5 by the oxygen plasma ashing processing. Then, the insulating film 6 is formed on the upper face of the multi-layer film substrate 31, using the plasma CVD method or the like. This insulating film 6 is formed on the upper face of the upper clad layer 5, on the upper
10 face of the ridge 12 and on the side of the ridge 12. The insulating film 6 may be a silicon nitride film.

Subsequently, as shown in Fig. 3A, the resist 11 is formed above the ridge 12 in such a manner that the resists rises above the ridge 12 in height. Spin coat or
15 the like is used for application of the resist 11.

Subsequently, as shown in Fig. 3B, a portion of the resist 11 is removed by the photolithography and oxygen plasma etching processing. The etching process is controlled in such a manner that the etching stops when
20 the insulating film 6 above the ridge 12 gets exposed.

Thereafter, for example, as shown in Fig. 3C, FREON-gas plasma etching processing is performed to remove the insulating film 6 on the upper face of the ridge 12. The etching process is controlled in such a
25 manner that the etching stops when the contact layer 9 is exposed. The thickness of the resist 11 at this stage is from 1.6 μm to 1.8 μm , as measured from the top of layer 6 (in the area away from the ridge), and is from 1.8 μm to 2 μm , as measured from the top of layer 5 (in the area
30 away from the ridge). Therefore, the resist 11 serves as a protective cover with respect to the insulating film 6 in a portion other than the ridge 12, when etching the

insulating film 6 on the upper face of the ridge 12.

The resist 11 is then dissolved and removed using a stripping solution, and the oxygen plasma ashing processing is applied to thereby remove the remaining
5 resist 11. As the stripping solution, one containing aromatic hydrocarbon, phenol and alkyl benzene sulfonate at a ratio of 6:2:2 may be used.

Next, the positive electrode 7 (see Fig. 1) is formed on the exposed face of the contact layer 9 and on
10 the insulating film 6 using a dry deposition process, a plating process, and several photolithography processing steps, as previously described above for the prior art device. The deposited conductive layer for electrode 7 generally comprises a first sublayer of an adhesive metal
15 (such as titanium - Ti) with a thickness of at least 75 nm, and a second sublayer of a gold-diffusion barrier layer (such as platinum - Pt) with a thickness of at least 75 nm. In preferred embodiments, both the adhesion sublayer and the barrier sublayer preferably comprise
20 substantially no gold (Au), each comprising not more than 5% of gold by weight, and preferably not more than 0.5% by weight. After electrode 7 is formed, a thick gold layer is plated over electrode 7 through a patterned plating mask, as previously described. The ionic
25 solutions and solvents which contact the metal electrode 7 after it is formed have the potential of eroding portions of the ridge if they infiltrate through the electrode 7. The forward mesa shape of the ridge according to the present invention, however, reduces the
30 stresses which cause cracks to develop in electrode 7, and thus reduces the occurrence of the infiltration and the occurrence of the erosion.

Next, the lower face of the semiconductor substrate 2 is milled and polished and, then the negative electrode 1 is formed thereon. Similar steps are used to form the negative electrode 1, including exposure to one or more 5 ionic developer solutions and one or more organic solvents. The milling process used to thin the substrate also uses organic solvents, and may sometimes use ionic developer solutions.

10 The dry deposition process may be performed by a vapor deposition apparatus or a sputtering apparatus, or the like, all of which are generically referred to as dry deposition apparatuses herein. The dry deposition apparatus comprises a deposition axis along which deposition material flows in low pressure gaseous 15 environment (e.g., near vacuum), and a holder for holding a substrate within the deposition field of the apparatus. In preferred practice of the present invention, the holder is capable of revolving about a center axis of the holder, this center axis being substantially parallel to 20 a normal vector of the top surface of the substrate which is held by the holder. The holder is oriented within deposition field such that its center axis is preferably inclined with respect to the deposition axis (i.e., the center axis and the deposition axis form a non-zero acute 25 angle.) This configuration enables the thickness of the electrode on the upper face and the thickness on the side face of the ridge 12 to be made substantially the same.

The multi-layer film substrate 31 formed by the above-described process is cleaved, assembled as a 30 module, and mounted to thereby complete the semiconductor laser device.

Fig. 4 is an enlarged sectional view of the ridge

portion of the semiconductor laser device according to the present invention. As can be seen clearly, the width of the ridge 12 increases gradually from the upper face of the contact layer 9 towards the upper clad layer 5.

5 That is, the side of the ridge 12 forms a forward mesa form. Therefore, stress applied on the ridge 12 can be dispersed very smoothly and effectively. As a result, erosion of the contact layer 9 or formation of cracks at the boundary between the positive electrode 7 and the
10 insulating film 6 are substantially reduced, and preferably prevented. Fig. 4 shows that the side faces of the semiconductor laser device are straight, however, the side faces may be curved so as to have concave surfaces, as shown in Fig. 5.

15 Fig. 5 is a diagram showing the distribution of aluminum (Al) in the composition of the ridge 12. The contact layer 9 is composed of p-type GaAs, and has a thickness of 400 nm. The upper clad layer 5 is composed of p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ($x_1=0.3$). The forward mesa forming
20 layer 30 is a p-type AlGaAs layer having a thickness of 30 nm, wherein the composition of aluminum is 0.3 ($x_2=0.3$) near the upper clad layer 5 and 0 ($x_2=0$) near the contact layer 9. The composition of aluminum in the forward mesa forming layer 30 (x_2) decreases
25 monotonically and substantially continuously from the upper clad layer 5 towards the contact layer 9. When the content of aluminum is more, the etching speed decreases. That is, the forward mesa forming layer 30 is etched
30 faster near the contact layer 9 than near the upper clad layer 5.

In general, forward mesa forming layer 30 may have a thickness in the range of 5 nm to 1000 nm, and more

preferably in the range of 25 nm to 100 nm, and most preferably in the range of 25 nm to 35 nm. In preferred embodiments, the thickness of layers 5 and 9 are greater than the thickness of forward mesa forming layer 30.

5 The positive electrode 7 has substantially the same thickness on the upper face and on the side face of the ridge 12. In other words, 200 nm thick positive electrode 7 is formed on the sides faces and the upper face of the ridge 12. This thickness is sufficient
10 enough to prevent formation of cracks or at the boundary between the positive electrode 7 and the insulating film 6, and erosion of the contact layer 9. In general, the thickness of electrode layer 7 is equal to or greater than 100 nm, and more preferably equal to or greater than
15 150 nm, and most preferably equal to or greater than 200 nm.

 The composition of the forward mesa forming layer 30 may be changed stepwise, e.g., in one or more steps. Fig. 6 is a diagram showing an embodiment in which the
20 composition of aluminum in the forward mesa forming layer is changed stepwise (two steps). The contact layer 9 is composed of p-type GaAs and has a thickness of about 400 nm. The upper clad layer 5 is composed of p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$. The forward mesa forming layer 30 is a p-
25 type AlGaAs layer having a thickness of 30 nm, wherein the composition of aluminum changes stepwise. In other words, in the forward mesa forming layer 30, the composition of aluminum changes from about 0.3 to about 0.2 near the upper clad layer 5, changes from about 0.2
30 to 0.1 in the middle of layer 30, and it is about 0.1 near the contact layer 9.

 When the composition of the forward mesa forming

ridge, but one may use a single continuous groove which encircles the ridge.

Furthermore, a ridge-type semiconductor laser device has been taken as an example of semiconductor
5 device in the above explanation. However, the present invention may be applied to, for example, a ridge guiding semiconductor photodetector.

Furthermore, a semiconductor laser device has been taken as an example in the above explanation. However,
10 the present invention can be widely applied to a general semiconductor device in which a multi-layer film is simply formed into a ridge shape by etching processing.

As explained above, according to the present invention, the ridge of the semiconductor device is
15 formed from the first, second, and the third semiconductor layers sequentially from bottom to top. The etching speed of the second semiconductor layer is higher than that of the first semiconductor layer and slower than that of the third semiconductor layer.
20 Therefore, precise machining can be performed by etching, cracks or erosion due to an abnormal shape can be prevented, and high yield can be realized.

Furthermore, the second semiconductor layer is formed in such a manner that the second etching speed is
25 variable and it increases monotonically from near the boundary between the first semiconductor layer to the boundary between the third semiconductor layer, preferably in either a continuous manner or a stepwise manner. Therefore, fine machining by etching can be
30 further performed with higher precision.

Furthermore, stoichiometric composition ratio of the second semiconductor layer is sequentially changed to

thereby make the second etching speed variable.

Therefore a change in the etching speed can be easily realized, machining by etching can be performed precisely, cracks or invasion due to an abnormal shape
5 can be prevented from occurring, and high yield can be realized.

Furthermore, the first semiconductor layer has a composition $Al_{x1}Ga_{1-x1}As$ where $x1$ is substantially constant, the third semiconductor layer has a composition
10 $GaAs$, and the second semiconductor layer has a composition $Al_{x2}Ga_{1-x2}As$ wherein $x2$ is a variable. This construction reduces, and preferably prevents, the occurrence of a reverse mesa form by creating a forward mesa form. In general, a reverse mesa slope can create
15 stress within the ridge, which in turn may cause cracks in electrode layer 7. (In the inventors' co-pending patent application Serial No. _____, they propose another invention for addressing cracks that may occur in reverse mesa ridges.)

20 Furthermore, an electrode layer is provided above the third semiconductor layer and covering at least the side of the ridge portion in the longitudinal direction, wherein the thickness of the electrode layer is equal to or greater than 100 nm, more preferably equal to or
25 greater than 150 nm, and most preferably equal to or greater than 200 nm. Therefore, occurrence of cracks caused by the stress applied on the electrode layer can be prevented, and invasion to the inside of the covering portion can be prevented.

30 The semiconductor device according to the present invention can be effectively and easily formed using the semiconductor device manufacturing method according to

the present invention.

Although the invention has been described with respect to a specific embodiment for a complete and clear disclosure, the appended claims are not to be thus
5 limited but are to be construed as embodying all modifications and alternative constructions that may occur to one skilled in the art which fairly fall within the basic teaching herein set forth.

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